Project ID: ace155

Low-Mass and High-Efficiency Engine for Medium-Duty Truck Applications

Qigui Wang/Ed Keating

General Motors

6/24/2021

Overview

Timeline

Project start date: 10/2019

Project end date: 12/2023

Percent complete: ~30%

Budget

Total project funding

- DOE share $7,007,878
- Non-Federal Share $3,294,329

Funding received in FY20

- $1,943,118

Funding for FY21 planned

- $1,530,743

Barriers/Technical Targets

Combustion Technology

- Advanced gasoline stoichiometric dilute combustion to achieve the target fuel economy requirement & deliver outstanding value to the customer

Materials Technology

- Lightweight, high performance, and low cost

Partners

Oak Ridge National Laboratory

The Ohio State University

Michigan Technological University

ECK Industries Inc

Project lead: General Motors

Relevance

Objective:

Develop a medium duty truck engine, compliant with EPA emission standards, utilizing advanced materials and combustion technologies capable of (relative to 2015 L96 VORTEC 6.0L V8 engine):

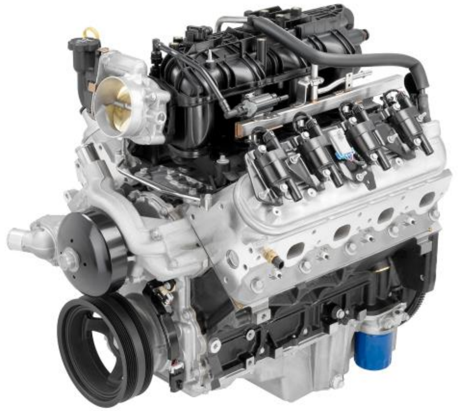
≥10% fuel economy improvement

≥15% engine weight reduction

Impact:

- The integrated R&D of advanced propulsion materials, manufacturing, and combustion strategies can not only expand engine operating efficiency, but also enable lighter weight engines for better performance and fuel economy.
- The technologies developed and demonstrated in this project will help bridge the technology gap between light and medium-duty engines.
- The approach and methodologies developed and implemented in this project can be readily applied to other material/component systems to shorten development time and cost.

Reduce energy usage and CO_2 emissions & increase energy security



2015 L96 6.0L V8 Engine (Baseline)

Chevrolet Silverado 3500HD truck with the baseline engine

Approach

Phase I - Research and Development | **Phase II - Validation and Demonstration**

2020 → 2021 → 2022 → 2023

Key Tasks

Task 1
- Simulate advanced combustion technology combinations
- Simulate durability at higher temperature and pressure
- Choose best combinations

Task 2
- Proof of concept physical testing using "basis" engine
- Develop materials and processes for Phase 2 testing on new engine
- Select technologies for Phase 2 new engine

Task 3
- Detailed design of new Phase 2 engine
- Fabricate parts for new engine
- Verify feasibility of new material and process innovations

Task 4
- Build and calibrate new engine
- Verify performance
- Post test evaluation of parts fabricated by new material and process innovations

Strategy & Work Streams

Fuel Economy Improvement: Simulation & Analysis → Engine Concept Testing

Weight Reduction: Simulation & Analysis → Engine Concept Testing

→ Design & Build Final Solution → Test & Validate Final Solution

Milestones

Month/Year	Description of Milestone or Go/No-Go Decision	Status
March 2021	Complete development and selection of lightweight high-performance materials (All)	Completed
June 2021	Develop advanced overcasting technologies (OSU)	On Schedule
Sept 2021	Complete development and optimization of materials and casting process for crankshaft (MTU)	On Schedule
Dec 2021	Go/No Go Decision #2 - Selected Engine Technologies Demonstrated Potential to Achieve Performance and Mass Objectives (All)	On Schedule
March 2022	Proposed medium duty truck engine hardware designed	On Schedule
June 2022	Key engine components produced with the developed material & manufacturing solutions	On Schedule
Sept 2022	Thorough process modeling and durability analysis using ICME completed	On Schedule
Dec 2022	Go/No Go Decision #3 - An initial assessment is completed as to the capability of the new concepts to meet or exceed the project targets	On Schedule

GM – General Motors, ORNL – Oak Ridge National Lab, OSU – Ohio State University, MTU – Michigan Technological University, ECK – Eck Industries Inc

Technical Accomplishments

Fuel Economy Improvement TASK 1 - 2020 (Technology Research & Development)

Potential engine architecture designs coupled with combustion system technology simulations

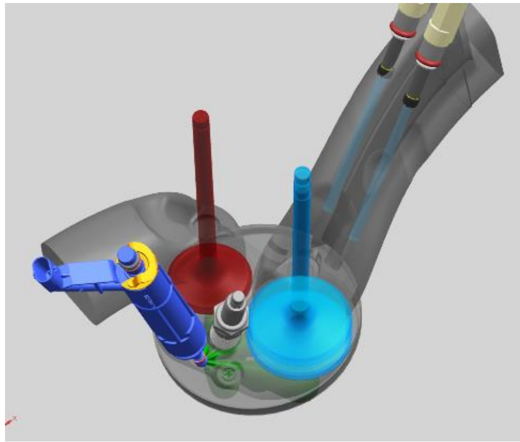
- **Layout and Performance Simulation of Engine Architectures (#1 Large Displacement, Normally Aspirated and #2 (Small Displacement, Boosted)**
  - ✓ Determine approximate overall engine displacement, cylinder size and number of cylinders
  - ✓ Execute basic layout of engine in medium-duty truck to understand packaging opportunities and challenges
  - ✓ Establish approximate cost differential of engine assembly
  - ✓ Employ 3D CFD analysis to create and evaluate potential combustion system design and technology enhancements
  - ✓ Use 1D model to baseline and add projected benefits of proposed combustion system technology enhancements developed through 3D CFD analysis
  - ✓ Select engine architecture for further development

Technical Accomplishments

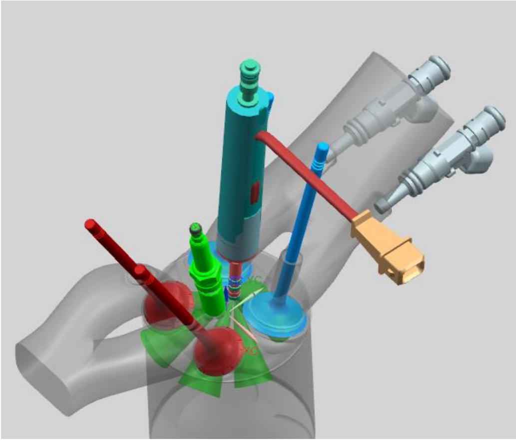
Fuel Economy Improvement TASK 1 - 2020 (Technology Research & Development)

Potential engine architecture designs coupled with combustion system technology simulations

- **Proposed Combustion System Technology Enhancements**
  - ✓ Advanced combustion system(s)
  - ✓ Optimal cylinder deactivation
  - ✓ Advanced valvetrain phasing and lift strategies
  - ✓ **Advanced fuel systems including "ultra" high pressure DI**
  - ✓ **Advanced ignition systems including pre-chamber**
  - ✓ Advanced EGR dilution systems including E-EGR
  - ✓ Atkinson or Miller cycle strategies
  - ✓ Variable induction system strategies
  - ✓ Combustion chamber cooling strategies



OHV 2-Valve Combustion System



DOHC 4-Valve Combustion System

Technical Accomplishments

Fuel Economy Improvement TASK 1 - 2020 (Technology Research & Development)

Potential engine architecture designs coupled with combustion system technology simulations

- **Methodology:**
  - ✓ Engine Architecture proposals were simulated using the PHASE 2 GEM simulation software.
  - ✓ The speed-load points of high fuel usage and impact on fuel economy based on this drive cycle simulation were established.
  - ✓ The top points, representing 90% of fuel energy used during the test cycle, defined the key operating points at which the fuel economy improvement potential was initially evaluated.

Weighted Fuel Economy Improvement

Technology	Specifics	6.6L NA V8	3.7L Turbo L6
PFI to DI	V8 update from Baseline	**1.9%**	base
Basic Architecture	6.6L NA V8 / 3.7L T L6	base	**7.5%**
Intake Valve Event	Atkinson / Miller	**2.5%**	**1.7%**
Cooled EGR	Dedicated EGR/LPL	**4.3%**	**2.1%**
Cylinder DEAC	Full Authority	**1.3%**	**0.1%**
UHPDI	1000 BAR Late Injection	**1.8%**	**1.7%**
Passive PC	Mult-hole small volume	**2.8%**	**2.1%**
Total		**14.6%**	**15.2%**

Technical Accomplishments

TASK 1 (Technology Research & Development)

MILESTONE 1.4 was completed in the 4th Quarter with the primary engine architecture selected

Primary engine architecture selection criteria per plan SOPO is noted below:

Milestone	Type	Description
Primary Engine Architecture Selected	Technical	Engine architecture selected based on potential to meet performance and weight objectives cost effectively

Primary Engine Architecture Selection Milestones:

Requirement/Attribute	Large NA V8	Downsized Boosted L6
+10% Fuel Economy	MEETS	MEETS
-15% Engine Weight	MEETS	MEETS
Estimated Engine Cost	BASELINE	**+37%**
Performance	MEETS	MEETS
Packaging	MEETS	MEETS

Primary Engine Architecture Selection Summary PUGH Chart

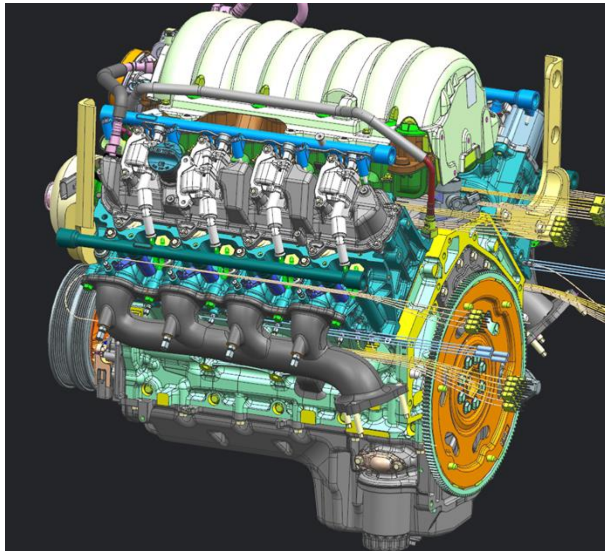
While both architectures show clear potential to meet the project objectives, our projection is that the large, normally aspirated V8 will do so much more cost effectively. Therefore, this architecture has been chosen for further development.

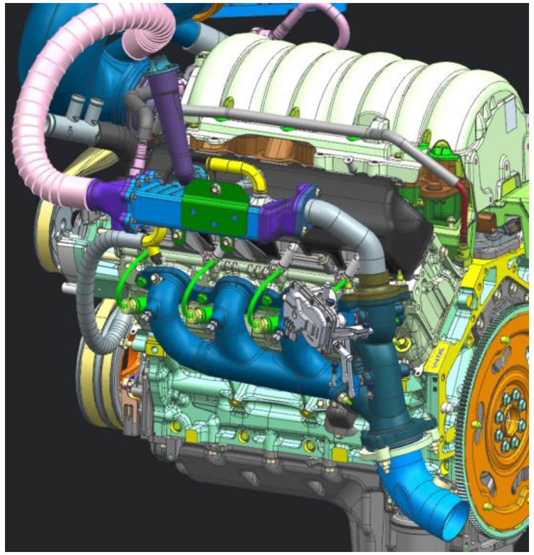
Technical Accomplishments

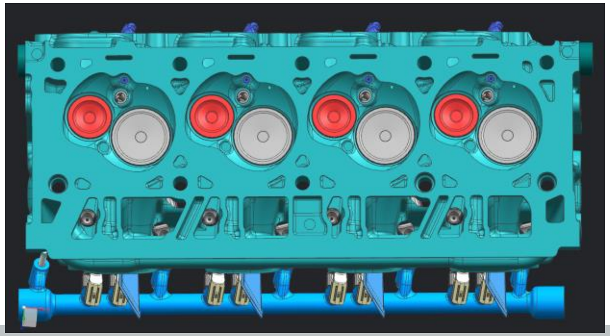
Fuel Economy Improvement TASK 2 - 2021 (Technology Research & Development)

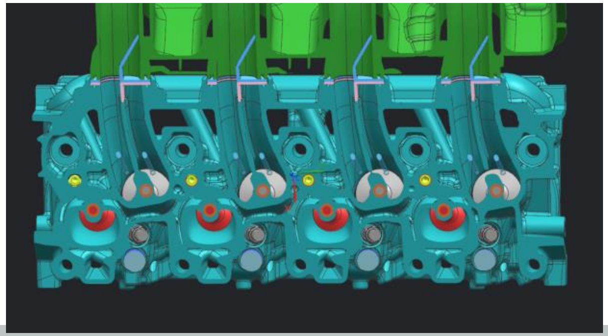
Design and build hardware to further develop TASK1 simulation predictions

- **Developed combustion system technology hardware to support test cell evaluation**
  - ✓ Advanced combustion system(s)
  - ✓ Advanced fuel systems including “ultra” high pressure DI
  - ✓ Advanced ignition systems including pre-chamber
  - ✓ Advanced EGR dilution systems including E-EGR
  - ✓ Atkinson cycle strategies
  - ✓ Variable induction system strategies
  - ✓ Combustion chamber cooling strategies









Technical Accomplishments

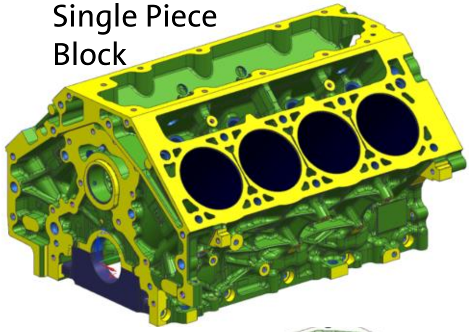
Materials and Manufacturing Solutions TASK 1 & 2 - 2020 & 2021 (Technology Research & Development)

➢ Mass Reduction Solutions

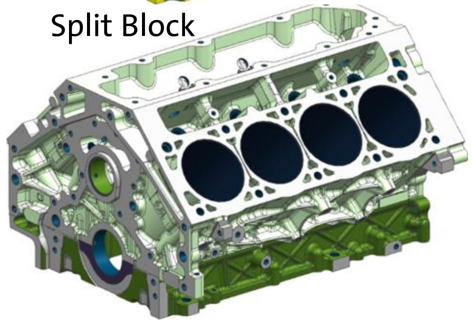
- ✓ New cast aluminum engine block to replace iron block & save up to 56.5% mass
- ✓ Hollow cast steel crankshaft to replace forged steel & save 1% mass & $$ saving
- ✓ Additive manufacturing (AM) piston to replace cast piston & save 2% mass
- ✓ Lightweight materials in oil pan, pickup tube assembly, oil pan cover, and block valley cover to save up to 42% mass

Model (kg)	S.P Block	Split Block	Crank	Piston	Others
L8T	108.11	108.11	25.77	0.436	7.59
DoE	***49.84***	***47.03***	***25.53***	***0.426***	***4.39***
Delta	58.27	61.08	0.25	0.010	3.2
% Reduction	**53.9%**	**56.5%**	**1.0%**	**2.2%**	**42.2%**

Single Piece Block

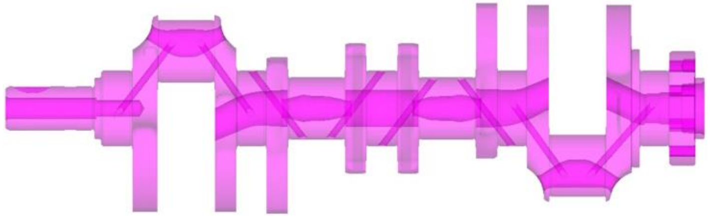


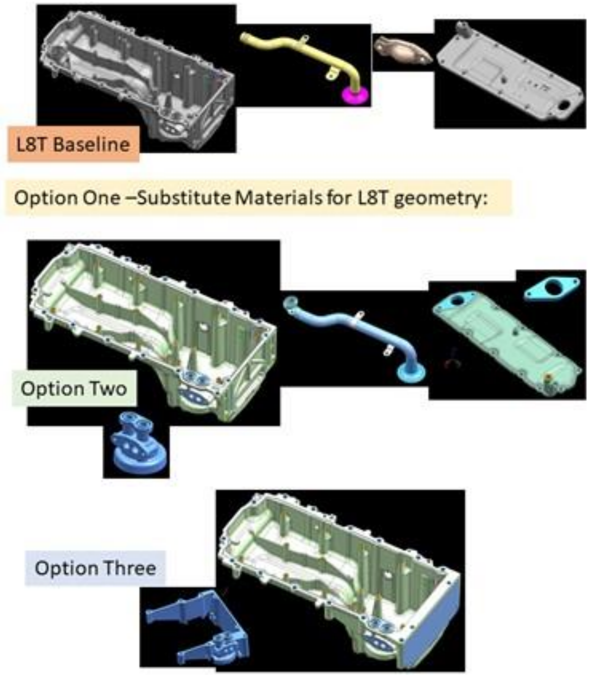
Split Block



Piston

Hollow Cast Steel Crankshaft



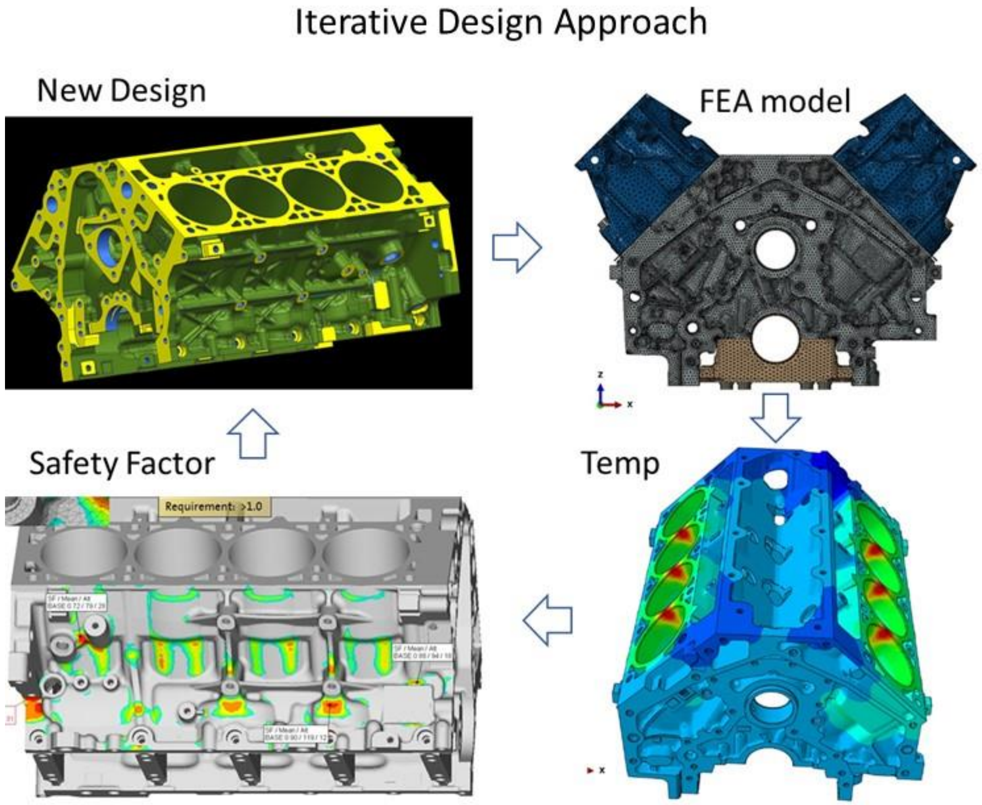


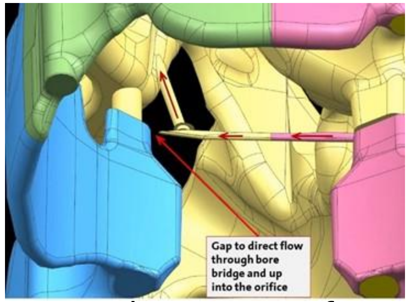
Technical Accomplishments

Materials and Manufacturing Solutions TASK 1 & 2 - 2020 & 2021 (Technology Research & Development)

➢ Cast Aluminum Engine Block

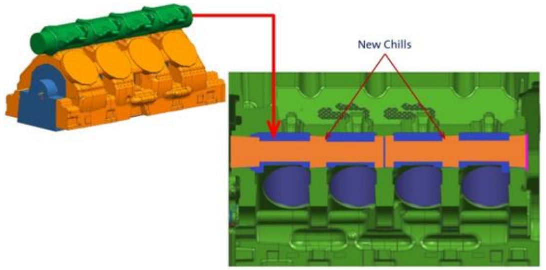
- ✓ New cast aluminum engine block designed at GM using iterative design approach and ICME tools
- ✓ Special sawcut and orifice geometry proposed and simulated to decrease block interbore temperature by 50°C
- ✓ Unique cambore chill proposed and evaluated numerically to refine local microstructure
- ✓ Alloy, casting/gating and process optimization started at ORNL, ECK and GM





Special sawcut & orifice

Design Level	Max B-Bridge Temp	
	LH	RH
DoE w/o sawcut	233	238
DoE w/Sawcut	208	206
DoE w/Sawcut + Orifice	**190**	**189**
DoE w/Sawcut + Orifice 1W	**187**	**186**

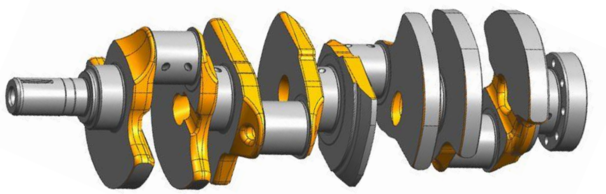


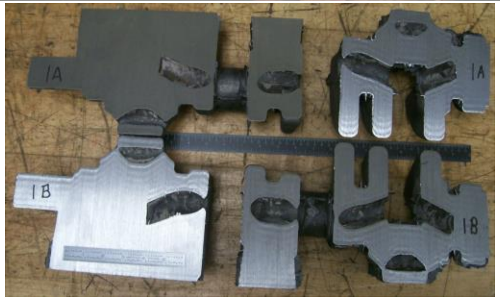
New Cambore Chill

Technical Accomplishments

Materials and Manufacturing Solutions TASK 1 & 2 - 2020 & 2021 (Technology Research & Development)

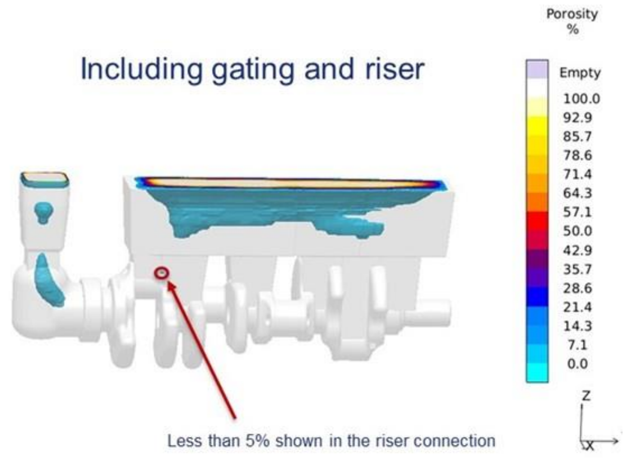
- **Cast Steel Crankshaft**
  - ✓ New hollow cast steel v8 crank designed at GM to replace forged steel crank using iterative design approach and ICME tools
  - ✓ Gating/riser system optimized at GM to eliminate macro-shrinkage defects
  - ✓ Three (3) high strength cast steel alloys evaluated and down-selected at MichTech (two from previous DOE cast steel crank project, one from GM pending patent)
  - ✓ Five (5) crank sand molds printed and poured with the down-selected alloy. Two cranks sectioned shows no macro porosity
  - ✓ Coupon tensile data from the crank casting heat showing excellent properties

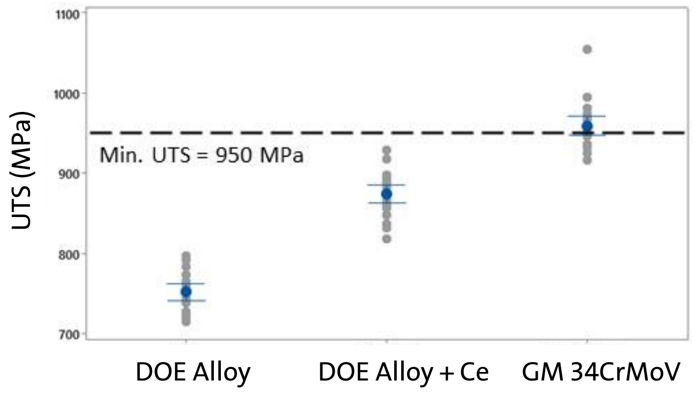




YS (MPa)	UTS (MPa)	Elongation
908.0	1014.9	11

Tensile properties of two coupons made from the same heat of 5 cranks





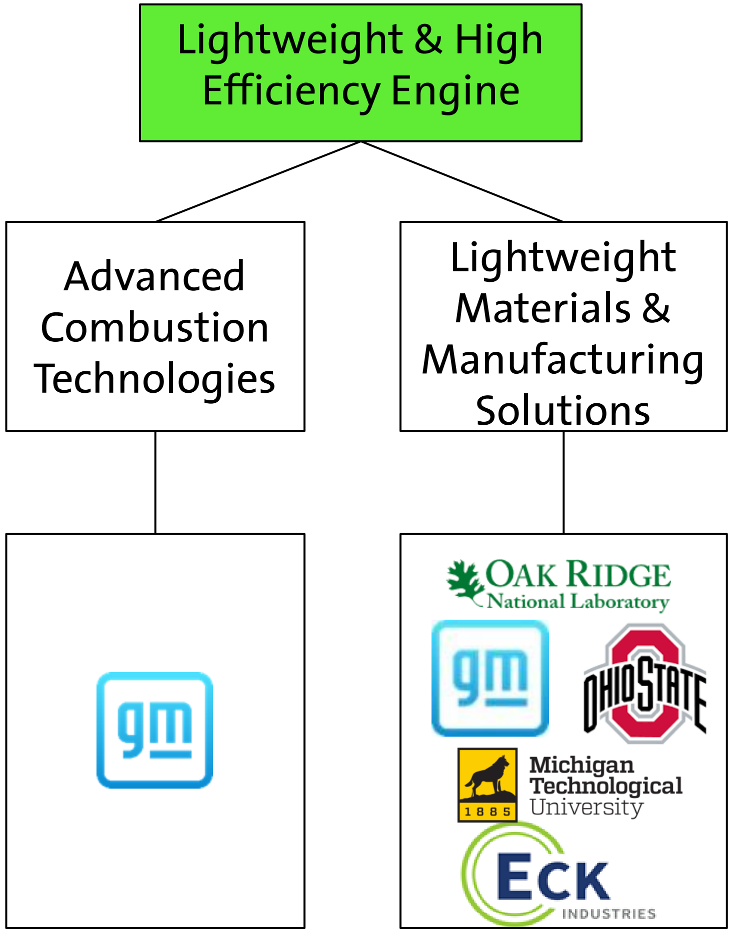
Three alloys evaluated

Responses to Previous Year Reviewers' Comments

- **"It would be interesting to see in the next annual report how ICME approach would be applied in order to accelerate development, reduce risk, and enable tailored properties that lead to cost effective mass reduction"**
  - ✓ Response: ICME has been applied in design and development of metal castings i.e. block, head, and crank through casting process optimization and local property predictions as reported in this AMR.
- **"Although very early in the project, already known barriers/challenges were not highlighted much. For example, initial crankshaft analysis demonstrated strength improvement but little weight saving. Peak cylinder pressures need to go up by roughly 50%, but block and head strengths are going to need much more work."**
  - ✓ More remaining barriers/challenges are highlighted in this AMR. Replacing a forged steel crank with cast steel/iron crank saves cost, but little mass saving is mainly due to design space constraints. High strength cast aluminum alloys developed from previous DOE programs are being evaluated and selected to fulfil the head and block strength requirements, coupled with new casting process developed in this project to eliminate casting defects and refine microstructure.
- **"Remainder of FY20 and FY21 research plans look good, although it's not really clear what the criteria for technology down select going into phase 2 will be based on if both meet the FOA minimum targets."**
  - ✓ Criteria for architecture down select and decision are reported in this AMR. Criteria for fuel economy technology down select will be assessed based on fuel economy benefit, weight, cost, engine performance impact and packaging.

Collaborations and Coordination

GM - Q. Wang, E. Keating, (prime) S. Campbell	Develop combustion technologies and high integrity low mass solutions; design, build and test new engine; CAE analysis, Virtual Casting, Project management
ORNL - A. Shyam, A. Haynes, (CRADA) A. Plotkowski, J. Simpson	Develop high strength high temperature Al alloys for head, block and piston & AM process for piston
OSU - A. Luo, M. Moodispaw (sub)	Develop overcasting technology for head valve seats, lightweight high entropy alloy (HEA), and computer simulation of defects in AM piston.
MTU - P. Sanders, S. Anderson (sub)	Develop cast steel and ductile iron alloys and casting technology for high performance crankshaft
ECK - D. Weiss, D. Hoefert (sub)	Develop novel casting technologies to cast high quality Al blocks and heads, cast-in-place inserts, casting simulation



Remaining Challenges and Barriers

- Advanced gasoline stoichiometric dilute combustion needs to achieve the target fuel economy requirement while delivering outstanding value to the customer.
- Peak cylinder pressure is expected to increase by up to 50% with 10% fuel economy improvement, which poses high demand in properties for key combustion components (block, head, crank and piston).
- Mechanical properties, particularly fatigue, of metal castings and AM parts are controlled by sizes of defects such as porosity and oxides. The new casting process being developed may face difficult to fully eliminate defects due to technology implementation constraints.
- New cast aluminum block design and analysis has shown significant mass saving and equivalent or better performance improvement, the long-term durability of new block aluminum alloys needs to be tested.
- Initial hollow cast steel crankshaft and AM piston design and analysis has demonstrated equivalent or better performance compared with forged steel crank and cast aluminum piston, respectively, but challenges remain in weight saving.

Proposed Future Work in FY21

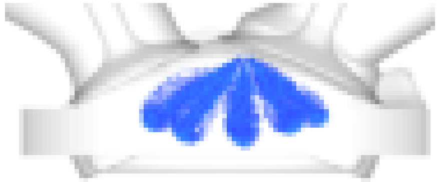
TASK 2 (Technology Research & Development)

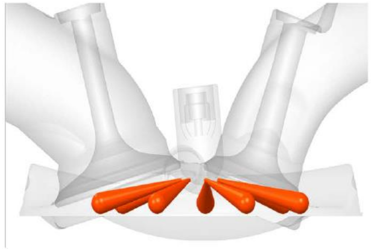
Evaluation and down-selection of proposed individual technology concepts using current equivalent architecture GM production or development engines

- **Task 2.1. Design and Build Hardware to Evaluate Advanced Combustion Technologies and Weight Reduction Techniques Using Current Equivalent Architecture**

- **Task 2.2. Test Cell Evaluation of Advanced Combustion Technologies and Weight Reduction Techniques Using Current Equivalent Architecture GM Development Engine**

  - Advanced combustion system(s)
  - Advanced valvetrain phasing and lift strategies
  - Advanced fuel systems including “ultra” high pressure DI
  - Advanced ignition systems including pre-chamber
  - Advanced EGR dilution systems including E-EGR
  - Atkinson or Miller cycle strategies
  - Variable induction system strategies
  - Combustion chamber cooling strategies



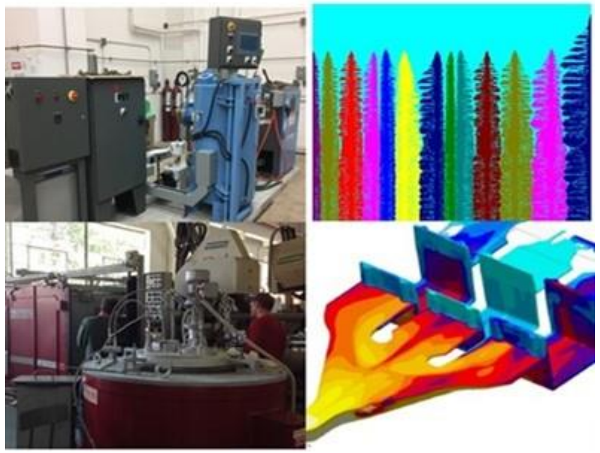


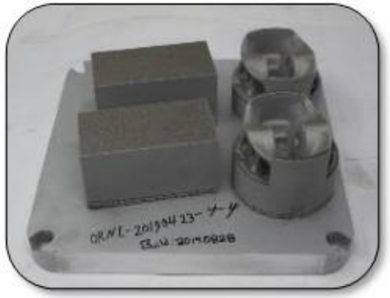
Proposed Future Work in FY21

TASK 2 (Technology Research & Development)

Evaluation and down-selection of proposed individual technology concepts using current equivalent architecture GM production or development engines

- **Task 2.3. Development of Advanced Material and Manufacturing Solutions for Mass Saving and Performance**
  - ❑ Develop and optimize single cast Al solution for head and block
  - ❑ Develop and optimize multi-material solutions for head and block
  - ❑ Develop and optimize material and manufacturing solutions for high performance piston
  - ❑ Evaluate and select high strength cost-effective cast iron alloy(s) for Al block liners
  - ❑ Develop and optimize material and manufacturing solutions for crankshaft
  - ❑ Conduct a Pareto study to choose the highest payoff materials and manufacturing technology options.





Summary

- This project involves large scale engine architecture design and analysis activity, advanced materials and manufacturing process development and down selection in the first year.
- Based on extensive simulation and analysis of fuel economy, mass, performance, packaging and cost, the normally aspirated large displacement V8 engine architecture was selected to meet project requirements with attractive performance, packaging and particularly cost attributes.
- Design and comprehensive performance analyses of key engine components identified such as cast aluminum engine block, cast aluminum cylinder head, cast steel crankshaft, and additive manufacturing (AM) piston have been completed, coupling with development and selection of new materials and manufacturing solutions.
- Remaining challenges and barriers have been identified together with future work plans to address the challenges to be able to achieve the FOA target fuel economy and mass reduction requirements in compliance with EPA emission standards.

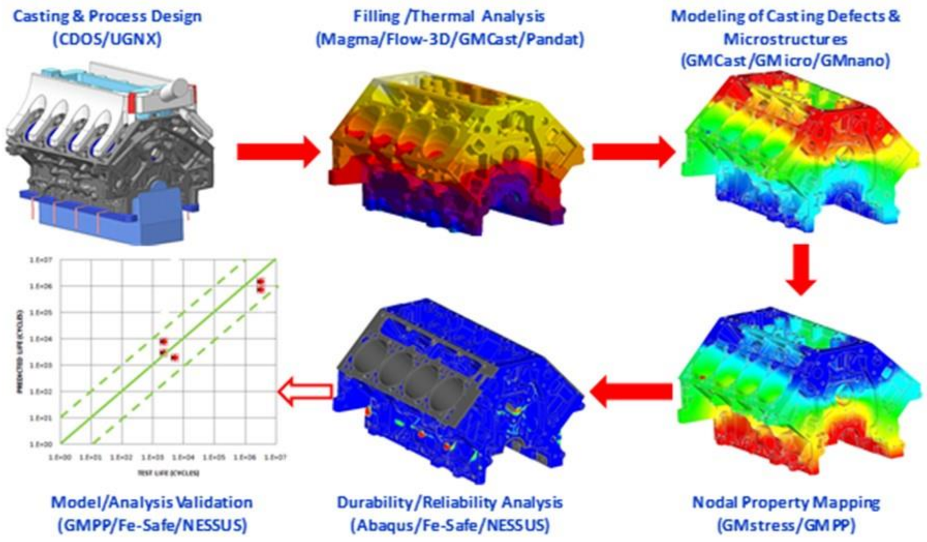
Technical Back-Up Slides

Approach

- The project begins with large scale engine architecture design and analysis activity, advanced materials and manufacturing process development and down selection. It culminates in an engine test cell evaluation with optimal materials and manufacturing solutions supporting final vehicle simulation. The final engine test will verify engine weight reduction and performance to the FOA objectives.

- The project is integrated with other research or deployment projects within the pertinent VTO subprogram. (https://www.energy.gov/eere/vehicles/annual-progressreports)
  - Advanced combustion engines (i.e. ace121, ace127, ace 133, etc.)
  - Propulsion materials (I.1.A, I.1.B, I.1.C, I.2.C, etc.) for cylinder heads & cast steel crankshaft
  - Lightweight materials (II.2.D, II.3.D, etc.) and LightMAT project (novel casting process development)

- Integrated Computational Materials Engineering (ICME) approach has been applied in this project to accelerate development, reduce risk, and enable tailored properties that lead to cost effective mass reduction.



GM Virtual Cast Component Development (VCCD)

Approach (Cont.)

- Integrate advanced combustion technologies with innovative material and manufacturing process.
- Assure that the higher thermal loads and cylinder pressures associated with efficiency gains can be practically implemented and leveraged by mass reduction.

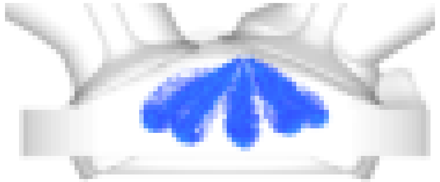
Lightweight & High Efficiency Engine

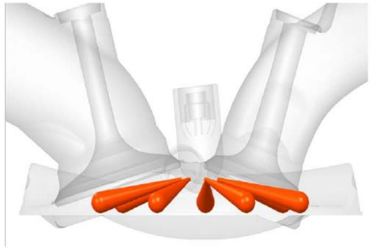
Advanced Combustion Technologies

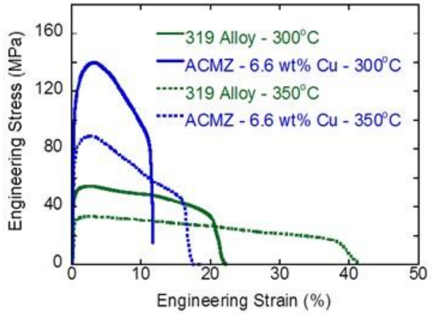
- Stoichiometric combustion focus
- Increased compression ratio
- Aggressive EGR dilution
- Load point optimization

Lightweight Materials & Manufacturing Solutions

- High strength Al alloys
- High strength cast steel
- High modulus ductile iron
- High entropy alloys (HEA)
- Additive manufacturing
- Novel Al casting process
- Overcasting





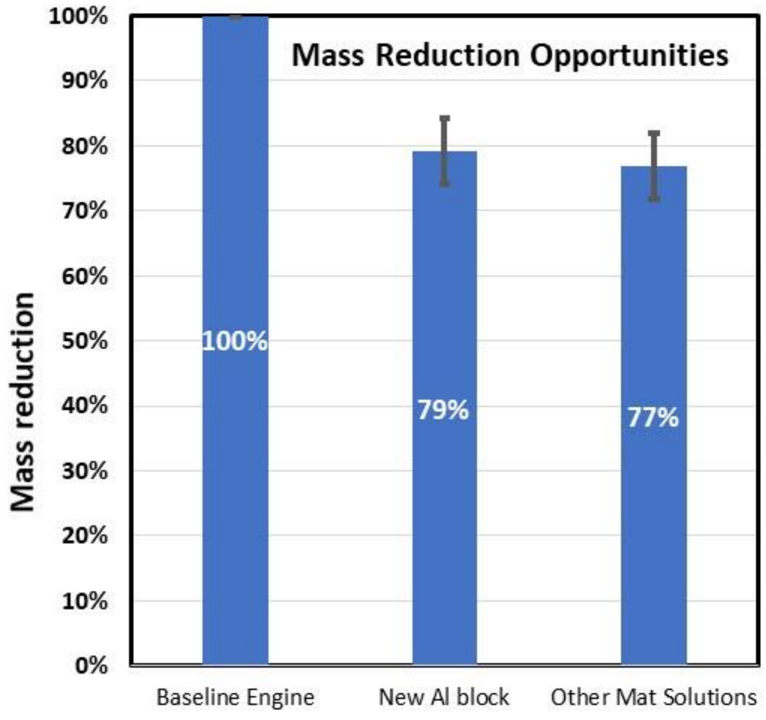


Technical Accomplishments

TASK 1 (Technology Research & Development)

MILESTONES 1.3 and 2.1 were completed in the 3rd Quarter 2020 and 1st Quarter 2021 with mass saving and high-performance material and manufacturing solutions developed for key engine components

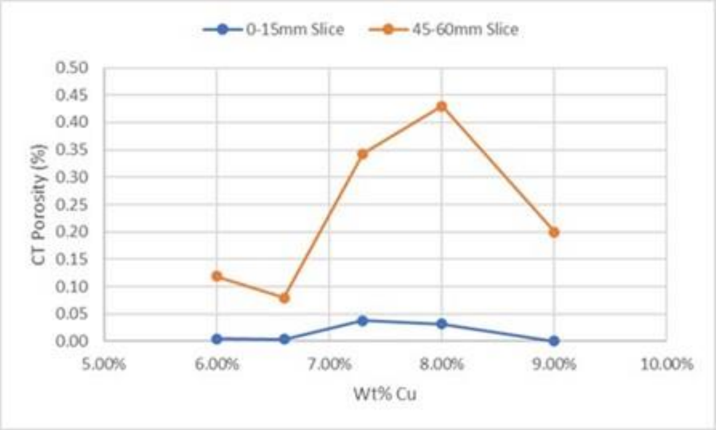
Mass Reduction & Performance Enhancement Materials and Manufacturing Opportunities			
Key Parts	**Baseline**	**Advanced Materials & Manufacturing**	
		Option 1	Option 2
Engine Block	Cast Grey Iron	High strength high temperature cast Al alloys	Single piece and split block designs, new casting process
Cylinder Head	Cast Aluminum 319	High strength high temperature cast Al alloys	Cast-in-place valve seats, new casting process
Crankshaft	Forged Steel	High strength cast steel	High strength high modulus nodular iron
Piston	Cast Hypereutectic Al	High strength high temperature Al for Additive Manufacturing	High entropy alloys (HEA) for Additive Manufacturing

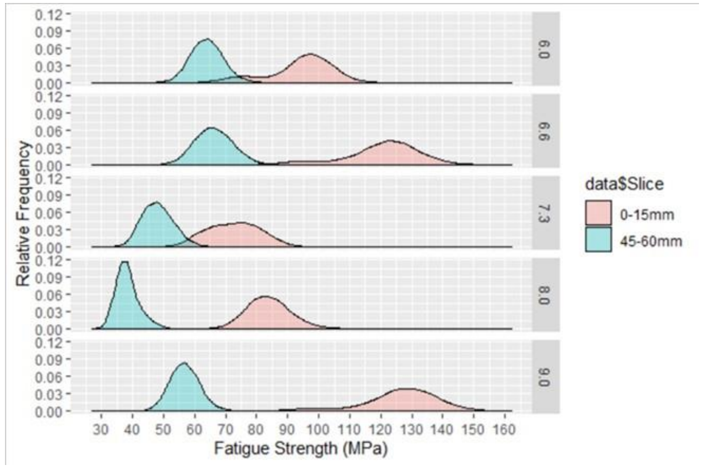


Technical Accomplishments

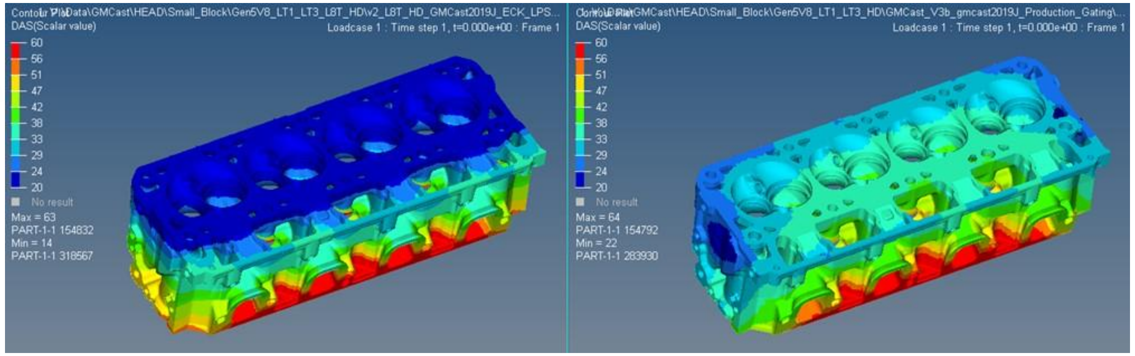
Materials and Manufacturing Solutions TASK 1 & 2 - 2020 & 2021 (Technology Research & Development)

- **Cast Aluminum Cylinder Head**
  - ✓ ORNL's ACMZ alloy with various Cu contents evaluated and down-selected based on castability
  - ✓ Fatigue strength predicted based on the X-ray CT pore size distributions and Monte Carlo simulations
  - ✓ A novel casting process proposed and evaluated numerically for cylinder head at ECK and GM
  - ✓ Optimal gating system/tooling design and process achieved with ICME tools at ECK and GM
  - ✓ As an example, the new process produces much finer microstructure compared with current production





New process tooling



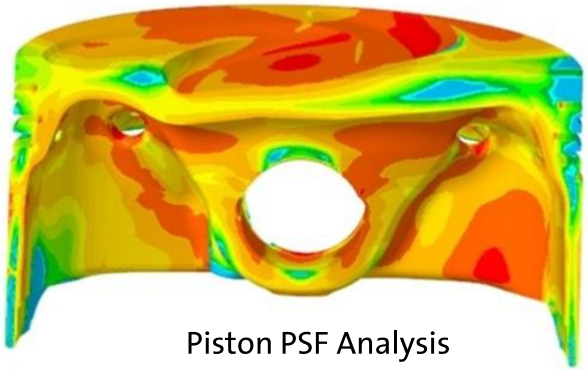
New Process

Current Process

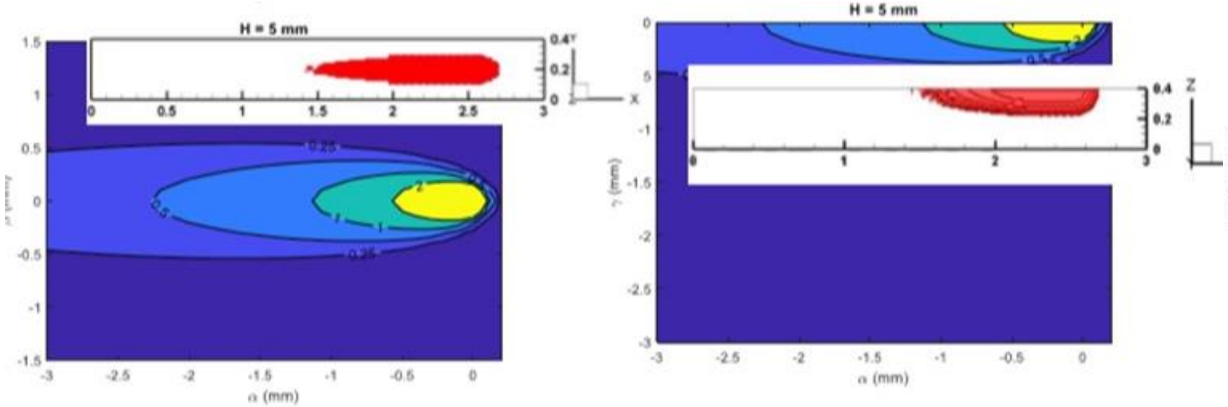
Technical Accomplishments

Materials and Manufacturing Solutions TASK 1 & 2 - 2020 & 2021 (Technology Research & Development)

- **Additive Manufacturing (AM) Piston**
  - ✓ Phase I piston design for AM completed, and passed CAE piston safety factor (PSF) requirement at GM
  - ✓ Alloys for AM piston evaluated and down-selected at ORNL, showing good properties
  - ✓ AM process optimization for the piston started with a GM piston at ORNL
  - ✓ AM process and microstructure modeling started at OSU



Piston PSF Analysis



AM Process Simulation